

A User Study Evaluating Level of Detail Degradation in the Periphery of Head-Mounted Displays

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Abstract. A user study was performed to evaluate the effectiveness of high detail insets used with head-mounted displays. Ten subjects were given a simple search task that required the location and identification of a single target object. All subjects used seven different displays (the independent variable), varying in inset size and peripheral detail, to perform this task. Frame rate, target location, subject input method, and order of display use were all controlled. Primary dependent measures were search time on trials with correct identification, and the percentage of all trials correctly identified. ANOVAs of the results showed that insetless, high detail displays did not lead to significantly different search times or accuracies than displays with insets. In fact, only the insetless, low detail display returned significantly different results. Further research is being performed to examine the effect of task complexity, and to reach a better understanding of the effect of varying inset size and level of detail.

Keywords. Immersive virtual environments, virtual reality, level of detail, head-mounted displays, usability, search

1. Introduction and Related Research

Virtual environments (VE) researchers have always been pushing their hardware to its limits. Initially, their efforts focussed on new modalities: how might natural head and body motion be incorporated into the human computer interface? How might the computer recognize a human gesture? But as the researchers found methods of incorporating these new modalities and began to attempt to combine them, they encountered a more traditional hardware limitation: the CPU. Despite resorting to the most sophisticated computer graphics machines, researchers still find it challenging to render complex VEs at more than a 15 Hz rate.

Many researchers have identified this "frame" or "update rate" problem as one of the most pressing facing the VE community [6, 9, 17, 29]. Foremost among the proposed solutions to this problem is the idea of varying "level of detail" (LOD). As used by most VE researchers, this phrase refers to model and rendering complexity, which can be varied to ensure that VEs are rendered at some minimal frame rate [11, 13].

Although such an approach does hold promise, careful consideration should be given not only to the computational costs of graphical rendering techniques, but also to their perceptual costs. If two rendering techniques make similar demands on the graphics engine, but the use of one of the techniques makes only a minimal contribution to

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perceptual fidelity or presence [12, 21, 23, 32], then that technique should be the first to go in the effort to maintain frame rate. Any other decision would clearly be wasteful.

This sort of consideration should not be limited only to evaluation of existing graphical rendering techniques, it can also suggest new ones. For example, perception is not uniform across the visual field. Many measures of ability to perceive detail, including visual acuity, contrast sensitivity, stereo acuity, and temporal sensitivity vary with retinal eccentricity [4, 10, 26]. In contrast, VEs often spread complexity and computation evenly across the raster display. This suggests the possibility of a computationally and perceptually efficient divided display containing a central, high detail inset, corresponding to the perceptual characteristics of the foveal area of the retina; as well as a surrounding, simpler periphery, corresponding to the perceptual characteristics of the peripheral area of the retina. We call this technique display division.

Howlett [14] and Slater & Usoh [24] have both proposed divided display systems, but the focus in their work was not improving frame rate. Both Funkhauser & Séquin [8] and Maciel & Shirley [16] have implemented systems that use display division. However, because both systems assume that the eyes are focussed on the center of the image, there is not necessarily a correspondence between the periphery of the retina and the peripheral areas of their displays. Furthermore, neither of these systems has undergone rigorous usability testing.

There are many rendering techniques that might be used to vary image complexity, including using geometric models of varying degrees of accuracy [7, 20, 28, 30], lighting models of differing levels of realism, and textures and graphics windows of differing resolution [16]. Many researchers have compared the relative importance of these and other graphical display techniques [2, 3, 5, 27]. In general, these studies showed significant effects on performance when image complexity is varied. However, in most cases a point of diminishing returns was reached, beyond which additional image complexity and computation produced insignificant performance improvement.

We chose to evaluate display division with the use of the computationally simplest of these techniques, varying window resolution. Moreover, because currently available eye tracking technology is unwieldy and expensive, we worked under the assumption that head-tracking alone would allow effective display division. In studies that examined varying resolution without display division, Booth et al. [5] found decreasing subjective preferences and increasing task performance times as window resolution was decreased. Smets & Overbeeke [25] showed that frame rate is more important than resolution for many tasks.

We believe that display division, when implemented in VEs, will result in minimal perceptual loss and significant computational gain. The computational portion of this assertion has already been examined in [8,16]. In our study, we attempted to verify the perceptual portion of this assertion by measuring subject performance time and accuracy while display division was used with varying inset sizes and levels of peripheral detail.

Because visual acuity and sensitivity decrease with eccentricity, we expected that loss of peripheral detail would have less impact on subject performance time and accuracy when display division was used than when an undivided, low detail display was used. We anticipated that use of the undivided, high detail display, which makes full use of available display resolution, would result in the lowest subject performance times and highest accuracies.

We had no way of predicting either the optimal visual extent of the high detail inset in the divided display, or the ideal LODs in the high detail inset and the periphery of the

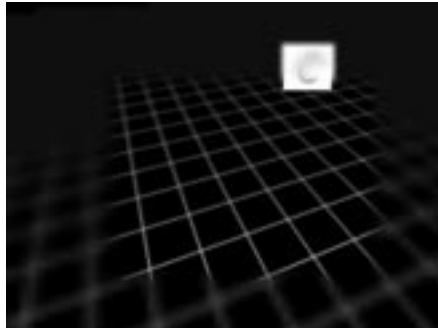


Figure 1: View of the target and floor in the experimental environment. Peripheral resolution is coarse, inset size is large.

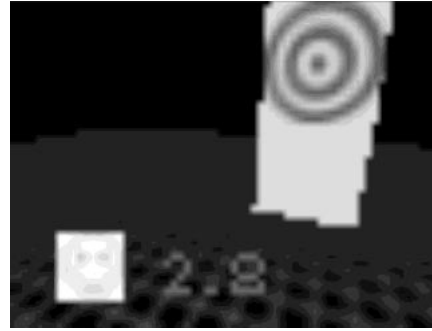


Figure 2: View of the home object in the insetless, coarse resolution display in the experimental virtual environment. Note the feedback for correct identification and search time.

display. We investigated the effect of varying these variables by using complex insets of two different sizes, and three different resolution levels.

2. Experimental Methodology

Ten college students, including both graduates and undergraduates, participated in the study. Two of the subjects were female. All subjects were experienced with virtual reality and head-mounted displays, and exhibited at least average corrected vision in testing. No subject wore glasses during the experimental sessions; subjects used contact lenses instead if optical correction was required.

Subjects wore a Virtual Research Flight Helmet [18,19] to immerse themselves in the experimental environment. The Virtual Research Flight Helmet mounts two color LCD displays on the user's head, each with vertical field of view of 58.4 degrees, and a horizontal FOV of 75.3 degrees. These two FOVs overlap across 60.6 degrees, giving the user a binocular FOV of 90 degrees. Each LCD contains an array of 208 x 139 color triads, with a resolution of 38.15 arcmin at the center of the field of view. The Flight Helmet weighs 3.7 pounds, and takes two NTSC signals as input. We used the Flight Helmet in a monoscopic mode by sending the same image to each of the video inputs, and mounting plastic fresnel lenses on the HMD optics to remove interocular disparity.

The motion of a subject's head in the Flight Helmet was tracked with the Polhemus Isotrak II 3D tracking hardware. The monoscopic images sent to the Flight Helmet were generated by a Silicon Graphics Onyx Reality Engine II, or on occasion a Silicon Graphics Reality Engine, using the gl graphics library and the SVE virtual environments library [15]. Silicon Graphics own scan converting hardware and software was used to convert these images into an NTSC signal. Subjects used a plastic mouse shaped like a pistol grip to respond to the experimental environment. The mouse had two buttons for the thumb mounted on top, and one button for the index finger mounted on the front. The mouse was not tracked. When using the experimental environment, subjects stood inside a 4x4 platform raised six inches and surrounded by a 3 foot railing. This kept subjects within four feet of the Isotrak transmitter.

The virtual experimental environment consisted of a floor, indicated by a grid of white lines on black (see figure 1). The background above the floor was also black. Users had no virtual body, that is, they could see no virtual analogue of themselves in the virtual experimental environment. Between trials, subjects would focus on a home object. The home object was a flat, white panel, labelled with a red bullseye design (see figure 2).

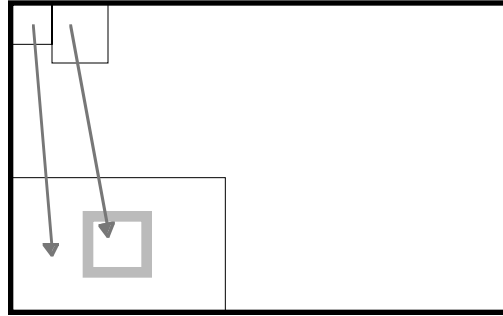


Figure 3: For insetted displays, two images are generated on the screen. One is textured into the periphery, one into the inset. The boundary is blended with transparency.

During each trial, subjects would search for a white target object, onto which a red uppercase letter (from A to J) or number (from 0 to 9) had been textured. The number 0 was distinguished from the letter O with a slash. The target always appeared at the same virtual distance, and subtended a horizontal visual angle of approximately 13 degrees.

LOD was varied by changing resolution (see again figure 1). When no high detail inset was used, a single image was generated with the required number of pixels, and then textured onto a 2D polygon with the screen size required by our scan converter. When a high detail inset was used, two images were generated with the needed numbers of pixels, and then textured onto two polygons: one for the low LOD periphery, and one for the high LOD inset. The two polygons were overlapped slightly and blended with alpha transparency to make the boundary of the high detail inset harder to detect (figure 3). Texturing was accomplished in real time with the `fbsubtexload` command and `FAST_DEFINE` [22]. Some computational efficiency was achieved by culling objects completely contained in the high detail inset out of the peripheral image. Since eye tracking was not used, insets were always located in the center of the displayed image.

With this technique, image generation was two to three times slower than the generation of constant resolution images without insets. However, our purpose in this study was not to derive a new LOD generation technique, merely to prototype a suggested LOD management technique and test its effectiveness. Furthermore, we believe that specialized rendering and scanning hardware, such as that suggested in [31], could make our generation technique a practical one.

Each experimental trial consisted of a single search task. After focussing on the home object, subjects pressed a button to begin the task. After a random (between .1 and .8 seconds) delay, the home object disappeared, and a single target object appeared outside the subject's initial view. Subjects located the target object and pressed one of two buttons to indicate if the object was labelled with a number or a letter. The target object then disappeared, and the home object reappeared. At the same time, onscreen feedback was provided indicating if the correct button had been pressed, and the number of seconds their search required. When the subjects had again focussed on the home object and pressed the appropriate button, a new search task began.

Subjects performed the search task with seven different display types. Each of these display types was a combination of the two main independent variables: peripheral resolution and high LOD inset size. Each of these variables was varied within subjects at three possible levels. The fine level of peripheral resolution of the image scanned into

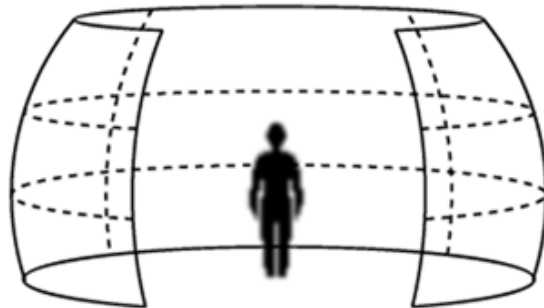


Figure 4: The search space around the subject was divided into nine regions. Targets were not located directly above or below the subject, or in view in home position.

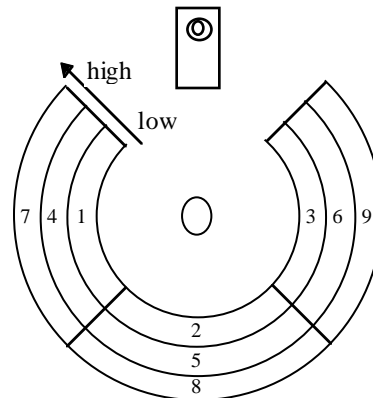


Figure 5: Top down schematic view of the user surrounded by the search regions. Here the regions are numbered in counterclockwise and low to high elevation order. The home object is at the top.

the HMD was 25% of NTSC: 320 x 240 pixels. Medium resolution was 9% of NTSC: 192 x 144. Coarse resolution was only 1% of NTSC: 64 x 48. Note that at all of these resolution levels, the image remained at a constant size.

The high detail inset was always presented at the fine level of resolution. The largest inset occupied one quarter of the display space (and had half the complete display's height and width). The smallest inset occupied only 9% of the available display space (with only 30% of the complete display's height and width). At the third inset size level, no inset was present. The size of the image generated for texturing into the inset was adjusted to ensure constant pixel size corresponding to the fine level of resolution. The seven different combinations of these variable levels used to create the seven different display types are listed in Table 1.

Several other variables were controlled. Since the maximum frame rates possible in the different display types varied, the minimum of these possible frame rate maximums was selected and used as an upper bound for the frame rates in all display types. This frame rate was 12, and the average resulting frame rate was 11.96, with an average standard deviation of .12. Target object location was controlled through the use of nine regions located around the subject, as illustrated in figures 4 and 5. These regions were of equal area, and no regions were located above, below, or in front of the subject when in home position. Care was taken so that targets would not overlap into neighboring regions. The letters or numbers on the target objects were randomly chosen. The button subjects used to indicated the presence of a letter (or number) was randomly varied and counterbalanced between subjects. Subjects worked with one display type until all trials with that display type were complete; however, the order in which different display types were presented was randomly varied between subjects, and counterbalanced so that no display was presented as the n th display three times, and so that no two display sequence was presented four times. Subjects were not permitted to end a trial unless the target object had actually been displayed on the HMD.

Display type was varied within subjects, with each subject using all seven displays. Each subject continued working with a display until 90 target objects were correctly identified (the letter or number was correctly identified), for a total of 630 correct trials over all

Table 1:

The seven display types. Performance with a display is shown as means and standard deviations for both accuracy (pctg correct) and search time (seconds on correct searches).

Display Type	Accuracy (pctg)		Srch Time (secs)	
	Mean	Std Dv	Mean	Std Dv
No inset, fine res	95.7%	6.74	2.652	0.793
No inset, med res	94.8%	6.84	2.863	0.878
No inset, coarse res	80.3%	12.85	3.490	0.993
Lg inset, med res periph	95.9%	6.11	2.986	0.825
Lg inset, coarse res periph	94.6%	6.90	3.146	0.930
Sm inset, med res periph	94.5%	6.90	2.727	0.790
Sm inset, coarse res periph	94.9%	8.08	3.097	1.033

display types. For the trials with a given type, the target object was located in each of the regions for 10 correct trials. The order of these region locations was random. For each trial, we recorded the date, time, subject, display type used, character on the target object, whether or not this character was a letter or number, the region in which the target object was located, the azimuth and elevation of the target object, the delay between the subject's indication that the trial may begin and the appearance of the target object, the time required to complete the search, whether or not the target object was correctly identified, and whether or not the target object ever appeared in the high detail inset. As noted above, the main dependent variables were search time on correct trials, and target identification accuracy. The between subject variables button assignment and display presentation order were recorded separately at the beginning of the experiment.

Before beginning the experiment, subjects read a two page introduction to the purpose of the experiment and its procedure. This explained, among other things, that subjects were permitted to pause between any two trials if they required a rest. It also made subjects aware that they would be ranked by search time and accuracy, with the subject with the best cumulative ranking receiving \$50 after the completion of the experiment.

Most subjects participated in three experimental sessions. Subjects were required to complete all trials with a given display before ending a session. Before beginning the first session, subjects were allowed 20 search trials as practice. At the beginning of each session, subjects were presented in sequence with five target objects located directly in the center of their view. This allowed subjects to reacquaint themselves with their button configuration. Before searching with a new display, subjects were allowed five practice search trials, so that they might familiarize themselves with the new display.

3. Results

The two primary dependent measures we used in our analysis of the results were accuracy and search time. Accuracy was defined as the percentage of correct search trials out of the total number of searches in a condition. Search time was the average time to find a target and make a correct identification.

Initially we performed a display type (7) by location (9) by button configuration (2) analysis of variance (ANOVA) on both accuracy and search time to discover if subject button configuration interacted with the other two independent variables. This analysis revealed no main effect or signification interaction. For all further analyses, this factor was collapsed over.

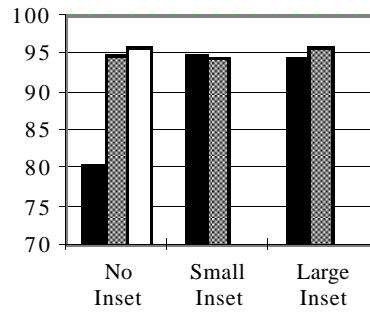


Figure 6: Average identification accuracy for each display type in percentage correct identifications. Displays grouped by inset size and peripheral resolution.

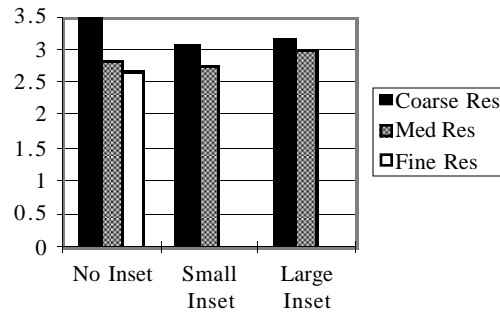


Figure 7: Average search times for each display type in seconds. Displays grouped by inset size and peripheral resolution.

We made two primary analyses. First we ran a display type by location ANOVA on accuracy. This analysis revealed only a significant effect of display type ($F(6,64) = 38.60$, $M_{\text{error}} = 0.00734$, $p < .001$). We used bonferroni pair-wise comparisons to determine which display types lead to different accuracies, using an adjusted probability level of 0.05. These comparisons revealed that all display types lead to significantly higher accuracies than the insetless, coarse resolution display condition (see table 1 and figure 6).

We next ran a display type by location ANOVA on search time. This analysis revealed a significant main effect of display type ($F(6,54) = 5.39$, $M_{\text{error}} = 1.347$, $p < .001$) and a main effect of location ($F(8,72) = 13.80$, $M_{\text{error}} = 1.213$, $p < .001$). The interaction between display type and location was not significant. Bonferroni pair-wise comparisons for display type revealed that the insetless, fine resolution display had significantly longer search time than the insetless, low resolution display. Furthermore, the insetted displays were not significantly different from the insetless, fine resolution display (see figure 7). The pair-wise comparisons for the main effect of location revealed that searches for targets in the three upper regions (7, 8 and 9 in figure 5) took significantly longer than searches for targets in other regions.

In an effort to investigate possible differences in accuracy and search time due to inset size and peripheral resolution, we ran a three-way ANOVA on these two variables. The factors in the analysis were peripheral resolution (2 levels) by inset size (2 levels) by region. Only location effects proved to be significant.

4. Discussion

Results indicated that peripheral LOD degradation can be a very useful compromise. The display type with the lowest LOD -- an insetless, low resolution display -- was significantly worse than any insetted display, even if the insetted display used low peripheral resolution. At the same time, the display type with the highest LOD -- an insetless, high resolution display -- was not significantly better than insetted displays of any type. The fact that these results were achieved without eye tracking is particularly interesting, and suggests that eye tracking may be of little importance in HMDs when the high LOD inset is not extremely small.

Unfortunately, we were not able to draw any conclusions about optimal inset size or LOD (in resolution) from our results. A trend relating increased LOD (in resolution) to decreasing search times did exist (figure 7), but was not significant. We suspect that this

is due to the nature of the experimental task. We hypothesize that search in this experiment involved two phases: motion to the area of interest, followed by closer examination. All peripheral resolutions proved adequate for the first phase. However, since even the smallest inset could contain most of the target object, peripheral resolution proved irrelevant in the second phase, and no significant effects of inset size or resolution resulted.

5. Future Work

Our hypothesis suggests that smaller inset sizes and larger areas of interest should increase search times. If an area of interest that fits into a screen but not into an inset is viewed, head motion rather than eye motion will be required during the identification phase, and search times will increase. We plan on testing this hypothesis in a followup experiment. The experiment will introduce a new variable, clusteredness, which measures the size of the area of interest. Through the use of this variable and a new, small inset size level, we hope to obtain some sense of the effect of varying inset size and peripheral resolution.

6. References

1. Adelson, E. & Bergen, J. (1984). Spatiotemporal energy models for the perception of motion. *J. Opt. Soc. Am. A* 2, 2, 284-299.
2. Atherton, P. & Caporeal, L. (1985). A subjective judgement study of polygon based curved surface imagery. *SIGCHI, Human Factors in Computing Systems, Conference Proceedings*, April, 27-34.
3. Barfield, W., Sandford, J. & Foley, J. (1988). The mental rotation and perceived realism of computer-generated three-dimensional images. *Int. J. Man-Machine Studies*, 29, 669-684.
4. Bishop, P (1986). Binocular vision. In Boff, K., Kaufmann, L. & Thomas, J. (eds.), *Handbook of Human Perception and Performance*, 1, Chapter 24, 619-689. New York: John Wiley and Sons.
5. Booth, K., Bryden, M., Cowan, W., Morgan, M. & Plante, B. (1987). On the parameters of human visual performance: an investigation of the benefits of antialiasing. *Computer Human Interaction and Graphics Interface Proceedings*, 13-19.
6. Bryson, S. (1993). Implementing virtual reality. *SIGGRAPH 1993 Course #43 Notes*, 1.1.1-1.1.5; 16.1-16.12.
7. DeRose, T. & Lounsberry, W. (1993). Multiresolution analysis of arbitrary topological types. University of Washington, Dept. of Comp. Sci., technical report UW-CSE-93-10-05.
8. Funkhauser, T. & Séquin, C. (1993). Adaptive display algorithm for interactive frame rates during visualization of complex virtual environments. *Computer Graphics (SIGGRAPH 93 Conference Proceedings)*, August, 247-254.
9. Furness, T. (1991). Virtual interface technology. *SIGGRAPH 1993 Course #3 Notes*, 8-11.
10. Graham, N. (1989). *Visual pattern analyzers*. New York: Oxford University Press.
11. Heckbert, P. & Garland, M. (1994). Multiresolution modeling for fast rendering. *Proceedings of Graphics Interface '94*, 1-8. May, 1994.

12. Heeter, C. (1992). Being there: the subjective experience of presence. *Presence*, 1, 2, 262-271.
13. Helman, J. (1993). Designing virtual reality systems to meet physio- and psychological requirements. In *Applied Virtual Reality, SIGGRAPH 1993 Course #23 Notes*, 5.1-5.20.
14. Howlett, E. (1992). High-resolution insets in wide-angle head-mounted stereoscopic displays. *SPIE Vol. 1669 Stereoscopic Displays and Applications III*, 193 - 203.
15. Kessler, D. (1993). The Simple Virtual Environment (SVE) library: user's guide. Technical report Gvu-93-24, Georgia Institute of Technology. For a more current description, see http document at <http://www.cc.gatech.edu/gvu/virtual/SVE>.
16. Maciel, P. & Shirley, P. (1995). Visual navigation of large environments using textured clusters. *Proceedings 1995 Symposium on Interactive 3D Graphics*, April, pp. 95-102.
17. National Science Foundation (NSF) (1992). Research directions in virtual environments. *Report of an NSF Invitational Workshop, Computer Graphics*, 26, 3, August 1992.
18. Robinett, W. & Rolland, J. (1992). A computational model for the stereoscopic optics of a head-mounted display. *Presence*, 1, 1, 45-62.
19. Rolland, J. & Hopkins, T. (1993). A method of computational correction for optical distortion in head-mounted displays. University of North Carolina, Chapel Hill, Dept. Comp. Sci., technical report 93-045.
20. Rossignac, J. & Borrel, P. (1992). Multi-resolution 3D approximations for rendering complex scenes. Technical report, Yorktown Heights, NY 10598, February 1992. IBM Research Report RC 17697 (#77951). Also appeared in the *IFIP TC 5.WG 5.10 II Conference on Geometric Modelling in Computer Graphics*, Genova, Italy, 1993.
21. Sheridan, T. (1992). Musings on telepresence and virtual presence. *Presence*, 1, 1, 120-126.
22. Silicon Graphics, (1993). Online man pages for the `fbsubtexload` and `texdef3d` commands on IRIX 5.X systems.
23. Slater, M. & Usoh, M. (1993a). Representations systems, perceptual position and presence in immersive virtual environments. *Presence*, 2, 3, 221-233.
24. Slater, M. & Usoh, M. (1993b). Simulating peripheral vision in immersive virtual environments. *Comput. & Graphics*, 17, 6, 643-653.
25. Smets, G. & Overbeeke, K. (1995). Visual resolution and spatial performance: the tradeoff between resolution and interactivity. *Virtual Reality Annual International Symposium '95*, 67-73.
26. Spillman, L. & Werner, J. (1990). *Visual perception: the neurophysiological foundations*. New York: Academic Press.
27. Todd, J. & Mingola, E. (1983). Perception of surface curvature and direction of illuminations from patterns of shading. *J. Experimental Psychology*, 9, 583-595.
28. Turk, G. (1992). Re-tiling polygonal surfaces. *Computer Graphics (SIGGRAPH '92 Proceedings)*, 26, 2, 55-63.
29. Van Dam, A. (1993). VR as a forcing function: software implications of a new paradigm. *IEEE Symposium on Research Frontiers in Virtual Reality*.

30. Varshney, A., Agarwal, P., Brooks F., Wright, W. & Weber, H. (1995). Automatic generation of multiresolution for polygonal models. *First Workshop on Simulation and Interaction in Virtual Environments*. July, 1995.
31. Yoshida, A., Rolland, J. & Reif, J. (1995). Design and applications of a high-resolution insert head-mounted-display. *Virtual Reality Annual International Symposium '95*, 84-93.
32. Zeltzer, D. (1992). Autonomy, interaction and presence. *Presence*, 1, 1, 127-132.